The Speed of Radio Waves and Its Importance in Some Applications*

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Summary—**This paper comprises a review of the present state of knowledge of the speed of transmission of radio waves under the practical conditions of certain applications in which such knowledge is important. It is shown first that, for radio waves in a vacuum, their speed of transmission is equal to the velocity of light (299,775 km/s), to within the limits of experimental error. When waves of frequencies in the neighborhood of 100 kc/s are propagated at a height of a fraction of a wavelength above the earth's surface, their speed is reduced by an amount dependent upon the electrical conductivity of the earth. For overland transmission, the speed is about 299,250 km/s. For higher frequencies propagated at a height of several wavelengths, the speed of the waves is determined by the refractive index of the air, rather than by the properties of the ground. Since the refractive index decreases with the height of transmission, so does the speed of the waves increase toward the velocity of light. For example, centimeter waves propagated at heights of a few hundred feet have been observed to travel at a speed of about 299,690 km/s. When the waves are transmitted between ground and aircraft flying at a height of 30,000 feet (9,800 meters) this speed is increased to about 299,750 km/s.**

I. Introduction

THE DEVELOPMENT of various radio applications in the past few years, such as the exploration of the ionosphere, radar, and various navigational aids, has given rise to an independent need for an accurate knowledge of the velocity of radio, as distinct from light, waves propagated under various conditions. It is the purpose of the present paper to give a brief review of recent investigations in the subject and the resulting state of our knowledge.

II. The Velocity of Light and Radio Waves in a Vacuum

(a) *The Velocity of Light*

Several independent reviews[1–4] of the results of direct measurements of the velocity of light have been made in recent years, some of these having been directed toward establishing the precise value of the velocity in vacuum, which is regarded as one of the most useful physical constants. It has been known and appreciated for a long time that the speed of light waves traveling through air or any other medium would vary with the permittivity or dielectric constant of the medium in accordance with Maxwell's original conception. But physicists have been a little perturbed by the suggestions made from time to time that the value of the velocity was varying slowly from year to year. The available evidence on this point was carefully considered by Birge[1] in his review of the General Physical Constants in 1941, and he concluded that the value of

$$299{,}776 \pm 4 \text{ km/s}$$

could be ascribed to the velocity of light in a vacuum, and that there was no satisfactory indication of any secular change in this value.

Another and rather more detailed review of the position was published in 1944 by Dorsey,[3] who with E. B. Rosa at the Bureau of Standards over forty years ago had determined the value of the velocity from calculations and measurements made on the capacitance of a capacitor of suitable shape. He confirms that the velocity of light in a vacuum is invariable but concludes that the best value for it is

$$299{,}773 \pm 10 \text{ km/s}.$$

From such considerations of the now classical experimental measurements of the speed with which light waves travel in a vacuum, we may conclude that this velocity is known to an accuracy of a few parts in 10^5, and that its value is less than the conveniently assumed figure of 300,000 km/s by about 750 parts in a million.

In the remainder of this paper, the value of the velocity of light waves in vacuum will be taken to be the constant:

$$c_0 = 299{,}775 \text{ km/s}$$
$$= 186{,}272 \text{ miles per second.}$$

(b) *Measurements on Radio Waves in a Vacuum*

Over twenty years ago, Mercier[5] described measurements of the velocity of electromagnetic waves guided by parallel wires in air. By making corrections for the assumed effects of the wires and atmosphere, a value for the resulting velocity of free waves in air was deduced.

Quite recently, Essen and Gordon-Smith[6] have considerably improved on this technique at the National Physical Laboratory in England, in the course of the development of cavity resonators for centimeter wave-

* Decimal classification: R111.1×R500. Original manuscript received by the Institute, April 15, 1949; revised manuscript received, August 5, 1949. Presented, 1949 IRE National Convention, New York, N. Y., March 9, 1949.

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[1] R. T. Birge, "The general physical constants," Reports on Progress in Physics, vol. 8, p. 92; 1941.

[2] R. L. Smith-Rose, "The speed of travel of wireless waves," *Jour. IEE*, part 1, vol. 90, pp. 31–83, January, 1943.

[3] N. E. Dorsey, "The velocity of light," *Trans. Amer. Phil. Soc.*, part 1, vol. 34, pp. 1–110; 1934.

[4] J. Warner, "The velocity of electromagentic waves," *Australian Jour. Sci.*, vol. 10, pp. 73–76; December, 1947.

[5] J. Mercier, "On harmonic and multiple synchronization," *Jour. Phys. and Radium*, vol. 5, pp. 173–179; 1924.

[6] L. Essen and A. C. Gordon-Smith, "The velocity of propagation of electromagnetic waves derived from the resonant frequencies of a cavity resonator," *Proc. Roy. Soc.*, vol. 194 A, pp. 348–361; 1948.

lengths. A cylindrical resonator was turned out of solid copper, and its internal dimensions were measured very carefully. From such measurements, the resonant frequency of the cavity can be calculated from the formulas for the propagation of waves in a cylindrical waveguide, and taking account of the well-known skin effect at the relevant radio frequency. This calculation involves a knowledge of the velocity of propagation of the radio waves inside this short, closed waveguide system. By measuring the resonant frequencies of the cavity for various modes, the above investigators were thus able to determine this velocity. The measurements were made with the resonator in a vacuum and led to a result of

$$299,792 \pm 9 \text{ km/s}$$

for the velocity of radio waves at a frequency in the region of 3,000 Mc/s.

This result obtained for a frequency of 3×10^9 cps (wavelength 10 cm) is about 17 km/s greater than that quoted above for light waves having a frequency of about 5×10^{14} cps (wavelength 6×10^{-5} cm). This difference is greater than the probable inaccuracy of either observation claimed by the workers at the two respective frequencies, so that it must remain for further investigation to resolve the apparent discrepancy in the determination of the physical constant denoted by c_0.

III. The Speed of Radio Waves under Conditions of Practical Application

The experiments just described refer to measurements made under laboratory conditions where, for standardizing purposes, the highest precision is required. Although it was long ago realized that, in the practical use of radio waves for communication and other purposes, the speed of travel of the waves would be affected by the transmission conditions over the ground and through the atmosphere, the need for a precise investigation of this subject has become increasingly apparent during the past decade.

In the first place, it is clear that the whole field of radar technique and its many applications is based upon a measurement of the time of transit of radio waves from a sender to a target and back to a receiver; and the distance of the target, which is one of the main factors required, can only be deduced with the aid of a knowledge of the speed of the waves.

Secondly, one of the most important results of the exploitation of radio-wave technique during the war years has been the development of new and improved aids to air and marine navigation. Some of these, such as the now well-known Gee and Loran methods, comprise a means of fixing the position of a radio-receiving point by determining the difference in time of arrival of pulse-modulated signals emitted in precise synchronism by two or more transmitting stations. Other systems such as Decca use continuous waves, and measure the same time difference of the arriving signals in terms of the phase difference of the carrier waves arriving at the receiver from two or more sending stations. In any of these cases, the time difference is measured by reference to a standard frequency of oscillation provided either by the transmitting station or incorporated within the receiving equipment. For the translation of time into distance, however, it is necessary to have a precise knowledge of the speed with which the waves travel between the transmitting stations and the receivers at which the measurements are made. In some applications, it will also be necessary to distinguish between the phase and group velocities of the waves. In the case of transmissions to aircraft, the velocity required may be that appropriate to the travel of waves through the air free from the effects of any obstacles on the ground, but subject to the effects, if any, of variations in atmospheric conditions such as density and moisture content. When the position finding is carried out on board ship, the waves will usually have traveled along the surface of the earth, perhaps partly over land and partly over sea, and it is necessary to know the speed with which the waves have traveled over the particular terrain forming the path between the transmitting and receiving points. In assessing the accuracy of such methods of using radio waves for position-fixing and navigational purposes, it is important to appreciate the limitations imposed by our knowledge of the speed of propagation of the radio waves, and it is already realized that there is need for further investigation on this subject if full advantage is to be taken of these important developments.

IV. The Speed of Radio Waves Transmitted over the Earth's Surface

In a review[2] of this subject made in 1942, the author drew attention to the results obtained some years earlier in the course of an investigation on the velocity of medium radio waves carried out in the USSR under L. Mandelstam and N. Papalexi. From the observations then available, it was concluded that limiting values of 299,000 and 299,500 km/s could be ascribed to the speed of such waves for transmission over a clear air path or over sea or fresh water. In the case of transmission over land, a somewhat lower value of 295,000 km/s was obtained, although this would appear to be subject to some uncertainty in determining the true path of transmission, owing to various intervening obstacles. In later work, the Russian authors have described their investigations into the nature of the electromagnetic field near an antenna, and the effect of distance on the speed of transmission. As pointed out by Ratcliffe,[7,8] the results of this work show that the velocity of the ground wave is less than the velocity in free space, provided we are not too far from the transmitter, and equal

[7] J. A. Ratcliffe, "The velocity of radio waves," *Proc. Union Radio Sci. Internationale* (Paris), vol. 6, p. 107; 1946.

[8] J. A. Ratcliffe, "A source of error in radio navigation systems which depend upon the velocity of a 'ground wave'," Proc. I.R.E., vol. 35, p. 938; September, 1947.

to that in free space at greater distances. These conclusions are consistent with the earlier calculations of Norton,[9,10] who has also pointed out the importance of knowing the ground-wave transmission conditions in the modern application of radio navigation systems. The work of the USSR investigators has also been supplemented by Eckersley,[11] in an investigation of coastal refraction effects. He claims that the theoretical explanation of this phenomenon is now satisfactory, and that what experimental evidence is available supports the conclusion that the refraction is only significant over a limited frequency range of from about 200 to 20,000 kc/s (wavelengths 15 to 1,500 meters), and that the effect disappears at distances sufficiently far from the coastal boundary. More recently, Millington[12,13] has described an investigation in this field.

While much of the work referred to above is of a quantitative nature, and indicates by how much the velocity of radio waves transmitted over land and sea is less than the value for free-space conditions, it is all of a rather low order of accuracy for the modern requirements of, say, a precise navigational system. It was in the course of the experimental use and calibration of such a navigation system that a method of finding the effective velocity of propagation of radio waves at frequencies in the region of 100 kc/s was developed by the British Admiralty Signal Establishment in 1945, and the results obtained by this method have been described by Mendoza.[14]

The measurements were made with the aid of a chain of three Decca transmitters operating on frequencies of 85 kc/s, 113.33 kc/s (4/3×85), and 127.5 kc/s (3/2×85) respectively; and observations were made in an airplane of the complete phase change experienced in flying round the system at a height of 1,000 feet (330 meters) which is about one-tenth of a wavelength above the ground. The measurements were made mostly at distances between 15 and 100 km along the extensions of the base lines connecting pairs of stations, but no significant change of readings with distance could be detected, nor were there any signs of dispersion within the limits of experimental error which were estimated at 1.4 parts in 1,000.

The mean value for the velocity of the radio waves determined under the above conditions was found to be

$$299{,}250 \pm 40 \text{ km/s}.$$

This is in good agreement with the results obtained several years earlier by the USSR investigators, although the precision of their measurements was much less. Also, as Ratcliffe pointed out in the discussion on Mendoza's paper, the above value of velocity would correspond from Norton's calculations to propagation over land having a resistivity of 3×10^3 ohm-cm (conductivity 10^3 electrostatic units). This would seem to be appropriate to the type of land over which the measurements were made.

Experience obtained in the use of another chain of Decca stations operated over land of lower conductivity (about 0.5×10^7 electrostatic units) has suggested that the velocity of the ground waves in this case was about 298,100 km/s; but these measurements are not of the same precision as those quoted above. When the propagation is over sea, the speed of the waves approaches that for free air transmission at the lower frequencies under consideration.

As is not uncommon in investigations of the type just described, the accuracy of the method is limited by the very observations which the navigational system is designed to avoid, namely, the determination of the position of the aircraft at the time of making the radio observations. This difficulty would naturally be increased in attempts made to repeat the measurements entirely over sea; although it is clearly desirable that, when practicable, the velocity measurements should also be made for conditions of transmission over sea. This, in turn, will lead to a more detailed study of transmission over a mixed land and sea path, which is a matter of great interest to those concerned with ground-wave radio propagation.[12,13]

V. The Speed of Very Short Radio Waves Transmitted through the Lower Atmosphere

It is well known that when electromagnetic waves travel through a medium of dielectric constant ϵ, their speed is inversely proportional to the refractive index n of the medium where $n=\sqrt{\epsilon}$. Thus when the waves, whether corresponding to light or radio frequencies, are transmitted through the air their velocity will be reduced to $1/n$ of the value in a vacuum. If we express n as equal to $1+\alpha$, then for air at the earth's surface in temperate latitudes, the value of α is of the order of 300×10^{-6}, but it may vary with temperature, pressure, and humidity from values of 400×10^{-6} or so down to negligibly small values, as the pressure decreases to zero. Thus we should expect the velocity of light in vacuum as given in Section II to be reduced to 299,675 km/s for transmission through air having a refractive index of about $1+350\times10^{-6}$ which corresponds approximately to a pressure of 760 mm, a temperature of 18°C and a relative humidity of 70 per cent.

Now the development of radar during the war led to

[9] K. A. Norton, "The calculation of ground-wave field intensity over a finitely conducting spherical earth," Proc. I.R.E., vol. 29, pp. 623–640; December, 1941.

[10] K. A. Norton, "A new source of systematic error in radio navigation systems requiring the measurement of the relative phases of the propagated waves," Proc. I.R.E., vol. 35, p. 284; March, 1947.

[11] T. L. Eckersley, "Coastal refraction," *Atti del Congresso Internazionale per il Cinquantenario della scoperta Marconiana della Radio*," p. 97, 1947.

[12] G. Millington, "Ground wave propagation across a land-sea boundary," *Nature*, vol. 163, p. 128; January, 1949.

[13] G. Millington, "Ground wave propagation over an inhomogeneous smooth earth," *Jour. IEE*, part III, vol. 96, pp. 53–64; January, 1949.

[14] E. B. Mendoza, "A method of determining the velocity of radio waves over land on frequencies near 100 kc/s," *Jour. IEE*, part III, vol. 94, pp. 396–399; November, 1947.

the use of some very precise methods of air navigation, and these have provided means of measuring the actual velocity of transmission through air for meter and centimeter waves. The results of such measurements, which have recently been published in England, have provided an experimental confirmation of this effect of atmospheric conditions on the speed of the waves.

The first series of measurements have been described by Smith, Franklin, and Whiting,[15] and were made with the aid of radio stations operating on the air navigation system G-H., at frequencies between 22 and 60 Mc/s. The technique adopted was to emit pulses of waves from an "interrogator" station, and these were received and re-transmitted from two "responder" stations at distances of 125 and 140 km respectively. The total time taken for the waves to go and return along each path was measured with the standard Gee equipment, steps being taken to determine and allow for the time of transit of the pulses through the equipment and feeders. Four experiments were carried out on separate days, and the observations indicated that the over-all accuracy was better than 2 parts in 10^4. Although the paths of the waves in the case of tests with one responder station were entirely over sea, while, in the other case, the path was partially over hilly land, there was no significant difference in the results obtained. It is considered, therefore, that the measurements apply to the velocity of meter waves through air at or near sea level, and the mean value obtained was

$$299,695 \pm 5 \text{ km/s.}$$

This is within the range of values expected from considerations of the atmospheric conditions referred to above.

The next series of measurements, described by Jones,[16] were carried out in a similar manner but with the range-measuring system known as Oboe. In this case the experiments, which were conducted in two parts, were made with pulse emissions on a wave frequency of about 3,300 Mc/s (wavelength 9 cm). The first series of measurements were made over two clear sea paths, 50 and 67.5 km long, using one control and two responder stations on the ground. As before, steps were taken to ensure that any time delays in the passage of the pulse signals through the equipment was allowed for, and it was found that there was no significant difference in the velocity measured over the two paths. Thus the mean value of several measurements was found to be

$$299,687 \pm 25 \text{ km/s}$$

which is in remarkably good agreement with the result obtained on meter waves under the same conditions of transmission over sea at ground level.

TABLE I

Height of Aircraft	*Mean Velocity*
10,000 feet	299,713 km/s
20,000 feet	299,733 km/s
30,000 feet	299,750 km/s

TABLE II

SUMMARY OF MEASUREMENTS OF THE SPEED OF RADIO WAVES

Authority	*Waves*		*Conditions of Transmission*	*Mean Value in km/s*	*Accuracy of Measurement*	
	Type	*Mean Frequency cps*			*km/s*	*Parts in 10^4*
Various	Light	5×10^{14}	In vacuum	299,775	± 10	0.3
	Radio	*Mc/s*				
L. Essen and A. C. Gordon-Smith	Continuous	3,000	In vacuum	299,792	± 9	0.3
L. Mandelstam and N. Paplexi	Continuous	1	Ground to ground	299,250	±300	10
E. B. Mendoza	Continuous	0.1	Ground to ground over land	299,250	± 40	1.3
R. A. Smith, E. Franklin, and F. B. Whiting	Pulsed	40	Ground to ground over sea	299,695	± 50	1.7
F. E. Jones	Pulsed	3,300	Ground to ground over sea	299,687	± 25	0.8
F. E. Jones	Pulsed	3,300	Ground to 3,300 meters Ground to 6,500 meters Ground to 9,800 meters	299,713 299,733 299,750	—	—

[15] R. A. Smith, E. Franklin, and F. B. Whiting, "Accurate measurement of the group velocity of radio waves in the atmosphere, using radar technique," *Jour. IEE*, part III, vol. 94, pp. 391–396; November, 1947.

[16] F. E. Jones, "The measurement of the velocity of propagation of centimeter radio waves as a function of height above the earth"; Part I, "Ground-level measurement of the velocity of propagation over a sea path," *Jour. IEE*, part III, vol. 94, pp. 399–402; November, 1947. Part II, "The measurement of the velocity of propagation over a path between ground and aircraft at 10,000, 20,000, and 30,000 feet," *Jour. IEE*, part III, vol. 96, pp. 447–452; September, 1949.

For the second series of experiments, the measurements were made between two ground stations and an aircraft flying at various heights. Although it was possible to make only a limited number of flights, the values obtained for the mean velocity of transmission between ground and aircraft were as listed in Table I.

These results confirm very well, indeed, the expectation that, as the height of the atmosphere through which the transmission takes place is increased, so does the speed of the waves tend toward the value at which they travel in a vacuum.

VI. Summary

The present state of our knowledge of the speed of radio waves may be summarized by the values given in Table II, in which the best known value for the velocity of light in a vacuum is included.